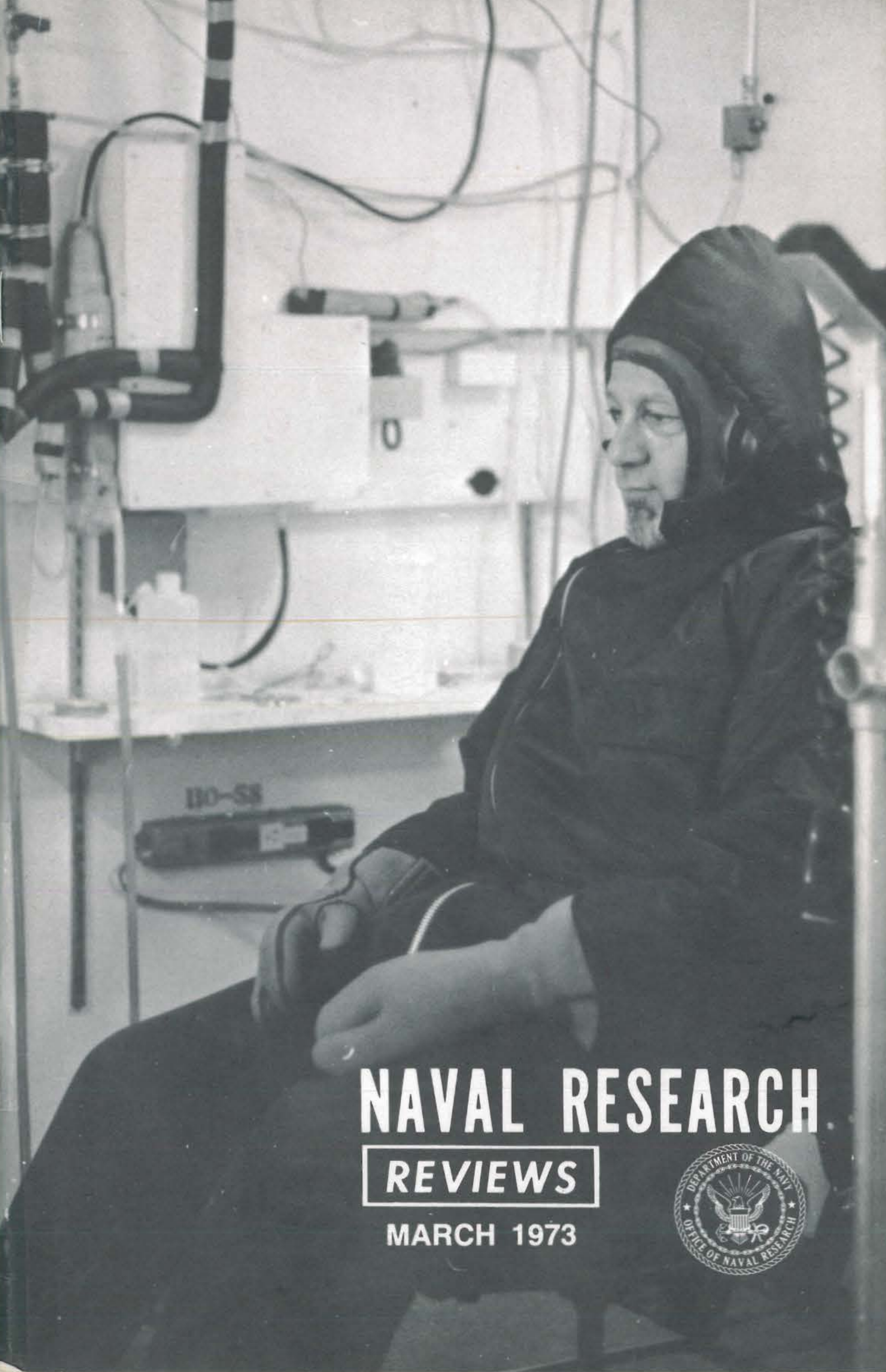

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Cover Caption

The diver seated in an environmental chamber is dressed in a dry suit. Underneath the suit is a garment of plastic tubes to warm the diver when returning to the chamber. *See page 1.*

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The Thermal Drain of Comfortable Hyperbaric Environments

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There is growing evidence that men living in hyperbaric conditions, whether in laboratory chambers or in saturation dives at sea, are under thermal stress like that of cold exposure, even though the temperature is in the "normal" range. An analysis I made two years ago pointed speculatively in that direction, but since then several studies have supported the idea that living in hyperbaric environments presents a considerable thermal drain. One of these was a 5-day saturation dive in a habitat at 516 ft (16.6 Ata) in warm Hawaiian waters, which turned out to be distressingly cold for the divers. Another was a 1200-foot (37 Ata) saturation dive in the hyperbaric chamber at the Institute of Environmental Medicine, University of Pennsylvania, where I helped in studying the thermal aspects of the environment. At the Fifth Symposium on Underwater Physiology at Freeport, Bahamas, in August 1972, Terry Moore and coworkers described a chamber dive in Hawaii where the habitat pressure was 16.1 Ata, but the gas temperature was kept up to the recommended level for comfort; and at about the same time the proceedings of the 1970 conference on hyperbaric and underwater physiology in Marseilles appeared, which contained a report on experiences in the German habitat Helgoland operated in the cold North Sea. Both of these exposures added to the evidence of thermal or metabolic stress. The Office of Naval Research has been supporting the author's work for several years.

The ocean saturation dive at 16.6 Ata at the Makai Undersea Test Range, Hawaii, was characterized by Jon Pegg, the medical officer, as producing divers who were almost continually cold and whose behavior was that of individuals under stress. The habitat temperatures were between 22 and 25 C, and the water temperature outside between 19 and 21 C. The 22 KW of heat available could not raise the habitat temperature higher. Contributing to the cold and discomfort was the failure of the hot water shower used for rewarming following a dive. At night sleeping was interrupted by shivering despite heavy covers. The divers estimated that they could have spent three times as much time outside

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if they had been able to rewarm adequately. Forty-five excursion dives were made, with an average length of about half an hour. Because it was impossible to rewarm, the divers could not comfortably make a second dive in the same day. As one expression of the cold stress, despite eating foods as desired, the divers lost an average of 2.9 kg (over 6 lbs) in weight, which Pegg felt should be attributed to increased metabolism due to excessive heat loss. This account of a saturation dive in the relatively warm waters off Hawaii emphasized two major points about living in hyperbaric environments. The first was that thermal comfort requires a higher-than-normal gas temperature, and the second was that men can apparently adjust to a steady thermal drain by increasing metabolic level, which causes weight loss.

Actually, cold is not felt in most saturation dives because the divers have gas temperatures of their choice, and they avoid feeling either cool or warm for the long days and nights of confinement. Chamber experiments have shown that hyperbaric gas must be kept quite warm.

Let us examine the comfort question more closely. When lightly clothed men are confined in a hyperbaric chamber of undersea habitat and allowed to choose the temperature in which they feel comfortable for days of exposure, the higher the pressure is the higher the comfort temperature must be, and the narrower the temperature band. Figure 1 shows this effect graphically. The scale of "convective character" is a device to arrange hyperbaric gas mixtures and other immersion fluids in a consistent manner. The density (in grams per liter) times the specific heat (in cal/gm-°C), times the thermal conductivity (in cal/min-Cm-°C) is divided by viscosity (in centipoises). Then this number is related to the number for air at 1 Ata, which is 0.61. In this scale of convective character, air becomes 1 and water becomes 167. In the 1200-foot saturation dive at the University of Pennsylvania, the four subjects who spent six days at this pressure chose a temperature between 32.5 and 33.5 C, and the convective character of that environment was 144. This new point would fall within the temperature range shown on the figure. Moore and his collaborators would agree, since their comfort temperature was 29 C for heliox at 16.1 Ata, and Pierre Varene and his coworkers in France have similar data for several pressures. Table 1 summarizes these observations.

Convective transfer increases remarkably with pressure, and the skin temperature is much closer to gas temperature than one observes for men in air. In the 1200-foot dive at the University of Pennsylvania, for example, the gradient between skin temperature and gas temperature was only about 2°C. Nevertheless, in these environments heat transfer from the skin to the environment is predominantly convective. In my previous analysis, it looked as though a fluid with a convective character of about 120 would cause a heat loss of 100 kcal/hr, approximately the normal

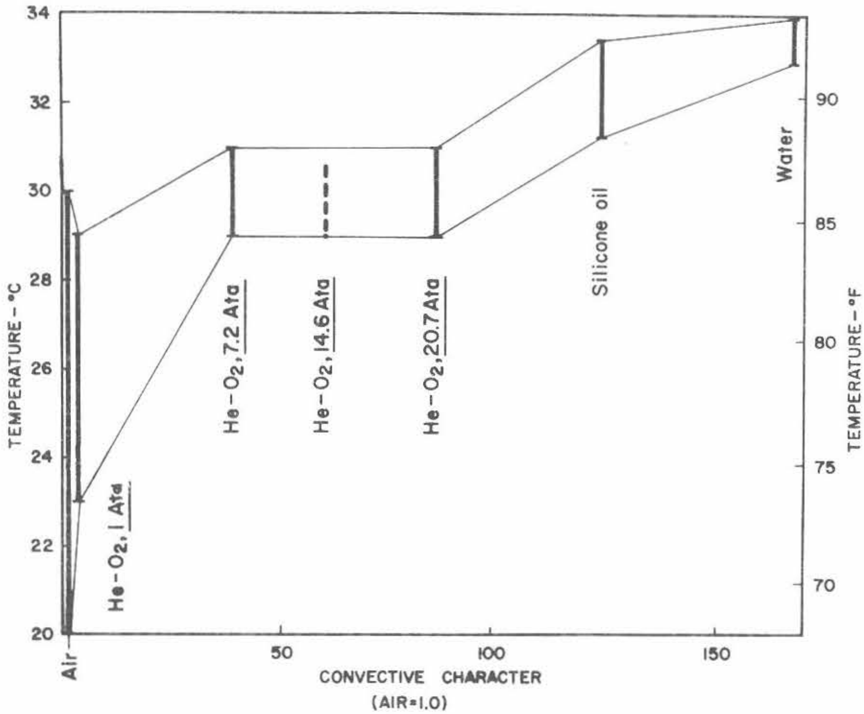

Figure 1 — Comfortable temperatures for prolonged stay in various fluids by men lightly dressed and mildly active. Based on data of Epperson, et al; Hamilton, et al; Hock, et al; Raymond et al; and Webb and Annis.

resting metabolism, despite the small temperature gradient. It that data can be extrapolated, the suggestion is that with fluids which are more convective—for example, the helioxygen at 1200 feet—convective drain would be higher than the resting metabolism despite the presence of a thermally comfortable gas temperature.

Let me describe the environment we observed in the 1200-foot saturation dive. At this pressure of 37 Ata, the temperature of the walls and various structures inside the chamber was virtually equal to gas temperature. The velocity of gas motion at several locations in the chamber was so low as to be undetectable using a wind vane anemometer. Significant gas motion was measurable only at the intake and discharge of the blower which circulated gas to the CO_2 scrubber. One could even see with the naked eye the leisurely gas motion and lethargic gaseous diffusion; when a different gas from that in the chamber—for example, a breathing mixture containing neon or nitrogen—spilled from a mask being held by a subject, the new gas with a different refractive index from that of helium could be seen falling slowly toward the floor, rather than immediately mixing and diffusing as one expects at lower

TABLE 1
Comfort Temperatures for
Normoxic Helium-Oxygen Mixtures
as a Function of Pressure

Gas Pressure Ata	Gas Temperature °C
1.5	28.7
2.3	29.6
4.4	30.0
8.4	30.7
13.1	28.5-31.5
16.1	29.0-31.8
22.2	29.0-31.5
28.3	30.0-32.0
30.8	32.4
37.4	32.5-33.5

pressures. We attempted to describe the evaporative character of the gas by measurements with a resistance hygrometer, with a wet bulb-dry bulb thermistory pair, and with a dewpoint hygrometer. All agreed that the humidity was high, probably above 90% saturation, despite the fact that dry gases were being added throughout the day and night and the fact that there were no large water surfaces or wet equipment in the chamber. We also observed the rate of weight loss of an open Petri dish and noted that it evaporated some 5 to 10 times more slowly than the same Petri dish would in air at 1 Ata. Low gas velocity and low diffusivity in a hyperbaric gas would explain the poor evaporative rate and the sense of high humidity which our subjects and those in similar dives report. In summary, the hyperbaric gaseous environment was warm, transferred heat well, did not move or mix easily, and prevented evaporative cooling on the skin.

The most direct evidence of an increased metabolic heat production is an increase in oxygen consumption. Such measurements have been made in four saturation dives in chambers, but while a small increase is consistently reported, it has not been enough to show that there is a significant rise in metabolism. However, these measurements have all been for brief 3 or 5 minute periods. What is needed is long term monitoring—preferably for 24 hours a day. Such data we do not have yet.

The most tangible evidence of thermal drain is the body weight loss observed in men who live in hyperbaric environments. Table 2 shows body weight losses from four saturation dives in laboratory chambers and four saturation dives in the sea. All dives were conducted in comfortable temperatures except for Aegir and Helgoland, both of which involved some exposure to cold. From the table it is evident that the higher the pressure and the longer the dive the greater the weight loss. The Aegir and Helgoland experiments are somewhat out of order in this sequence, but their higher weight loss for the pressure and duration shown can be ascribed to the increased heat drain of the cold environment. The table also shows what was known about food intake. Where estimates were made, the dietary consumption was generous. During the University of Pennsylvania 1200-foot dive, a serious effort was made to count calories, and the average level of 3510 per man per day should have prevented weight loss in young men who were cooped up in the small space of a hyperbaric chamber.

There is a bit of biochemical evidence that suggests increased metabolism in hyperbaric helium. In saturation dives in U.S. Navy chambers at San Diego and at the Experimental Diving Unit in Washington, D.C., a reduction of the level of blood glucose during saturation dives was reported, along with an increase in serum lactic acid and a decrease in serum free fatty acids. Such changes in blood chemistry are consistent with an increased carbohydrate metabolsim.

One additional curious observation may be part of this picture of increased metabolic activity. The body temperature, measured either in the rectum or by mouth, was reportedly about 1°C higher than normal during the Tektite and Sealab II experiments. In the 1971 University of Pennsylvania dive to 1200 feet, early morning rectal temperatures were found to be consistently elevated in all four subjects. However, midday rectal temperatures were not higher than expected. In fact, when two of the subjects exercised rather vigorously for 30 minutes, their rectal temperatures did not rise, suggesting that the increased heat production of exercise was rapidly drained in the highly convective environment. If the early morning rectal temperatures are high, then perhaps this indicates a higher-than-normal level of metabolism during the night. Further, as a guess, it may be that the usual diurnal variation of body temperature does not occur if the hyperbaric environment drives metabolic heat production to a constant, slightly high level.

Such are the lines of evidence to indicate that subjectively comfortable hyperbaric environments represent a thermal drain. That drain is met by an increased metabolic heat production in order to maintain body temperature. Despite high levels of food intake, men are not in caloric

TABLE 2
Body Weight Loss in Several Hyperbaric Saturation Dives

	Gaseous Environments	Mean Weight Loss (kg)	Food Intake (kcal/day)	No. of Subjects	Duration	
					At Depth (days)	Total Dive (days)
Tektite I (Caribbean)	Air- 2.15 Ata	1.6	"adequate"	4	60	
Helgoland (North Sea)	Air- 3.3 Ata	3-5	6000	9	10	
Genesis E (dry)	HeO_2- 7 Ata	0.6	4200	3	12	
U. of Hawaii (dry)	HeO_2- 16.1 Ata	0.6	>4000	6	2	9
Sealab II (Bermuda)	HeN_2O_2- 7.2 Ata	2	>4000 (est)	28	15	
Aegir (Hawaii)	HeO_2- 16.6 Ata	2.9	as desired	6	6	14
USN-EDU (dry)	HeO_2- 19.2 Ata	1.2	as desired	7	8	16
U. of Penna. (dry)	HeO_2- 37 Ata	4	3510	4	6	21

balance and they lose weight. Definitive experiments are needed to establish the actual pathway or pathways of increased heat loss, the magnitude of the metabolic response, and the physiological nature of what appears to be a real nonshivering thermogenesis in man.

Finally, we might consider the implications of the persistent loss of body weight observed in men who are apparently unwilling to eat enough food to meet their caloric requirements. Let us assume that the men in the 1200-foot saturation dive at the University of Pennsylvania needed approximately 3000 kcal/day to maintain their weight in the confined space of the chamber in the gas had been air at 1 Ata. Judging from the weight they lost in the 37 Ata heliox environment, they had a caloric deficit of about 1500 kcal/day; in other words, they should have been eating about 4500 kcals per day instead of the 3500 they actually consumed. If this had been an ocean dive, one would have to allow for the caloric demands of the exercise of excursion diving and possible extra heat loss in cold water, and the caloric need might well have risen to 6000 kcal/day—an amount that the divers in the German Helgoland habitat managed to consume. Such intakes are not unheard of for lumberjacks, who work hard and regularly consume such quantities, but with the exception of the divers in the Helgoland project men in undersea shelters have shown no desire to eat this heavily. In actual diving, a way must be found to supply such quantities and to encourage men to eat them, especially as saturation dives become longer. The weight loss is not necessarily bad for men who carry excessive body fat, but it could be a problem for thin men who need the insulation of subcutaneous fat for protection when diving in cold water. Supplying adequate nourishment to divers could become an increasing problem as the depth and duration of saturation dives continues to increase.